APPENDIX H
COPATH:
DESCRIPTION OF A SPREADSHEET MODEL FOR THE ESTIMATION OF CARBON FLOWS ASSOCIATED WITH FOREST USE[1]

Willy Makundi, Jayant Sathaye, and Andrea Ketoff
Lawrence Berkeley Laboratory

BACKGROUND

The importance of tropical forestry to global climate change has significantly increased as the world realizes the magnitude of greenhouse gas emissions emanating from deforestation. The crudest estimates indicate that conversion of tropical forests into other landuses contributes about a third of the anthropogenic CO_2 emissions.The potential for mitigative effects through conservation and reforestation has further heightened the need to better understand the dynamics of tropical forestry and their implications to global climate change. Various estimates of CO_2 emissions by different scientists reveal the extent to which we do not know the nature, extent and rate of increase of biotic greenhouse gas emissions.

Although there is a broad agreement on the general interplay between greenhouse gases in the atmosphere and climate, there is more uncertainty in the quantities of green house gases released from the use of forest resources, especially from tropical deforestation and degradation. Similar uncertainty exists with regard to the amount of carbon sequestered by forests, forest soils and forest products. Overlaying the two areas, more uncertainty surrounds the extent of the impact of both CO_2 fertilization and climatic change on plant growth, migration and feed-back into the carbon cycle. The main reason for this uncertainty is lack of precise data on the constituent variables required for the estimation. Such information includes classification of botanical ecosystems, biomass density, the rate of change of the biomass density through growth and removals, amount and capacity of edaphic storage and release of greenhouse gases, and the extent of storage and release through forest products.

The estimates of carbon emissions from deforestation in the tropics have varied widely over the past decade. Estimates of the extent and rates of deforestation by various researchers bear this fact out. Myers (1980) estimated that the tropical forest biome was losing about 200,000 sq. km. annually, of which about a half was considered to be totally destroyed, and the other half was expected to have a partial recovery after being used for shifting agriculture. FAO/UNEP (1981a,b,c) reports gave an estimate of 73,000 sq. km. of tropical forests annually being converted to other landuses. Melillo *et al,* (1985) and Molofsky *et al,* (1986) have shown that definitional and classificational discrepancies were partially responsible for the different estimates. In 1988, FAO claimed that there was little evidence of accelerated deforestation (Singh, 1988), while other

---

[1] COPATH was developed by the authors at the Lawrence Berkeley Laboratory, and has been used by F-7 network researchers to estimate carbon flows in their respective countries. The model is in the public domain, and is available on diskettes upon request. This work was supported by US Environmental Protection Agency, Office of Policy Analysis, Division of Global Climate Change.

researchers such as Myers (1984, 1985, 1988) and Houghton *et al* (1985, 1987) were arguing that the rate was increasing. Myers (1989) estimated that the tropical deforestation had increased to 142,000 sq. km. per year. Whereas Myers estimated that Brazil was losing 50,000 sq. km. per year by 1989, a Brazilian Space Research Agency report (INPE/IBAMA) estimated a loss of 25,000 sq. km. per year (Goldemberg, 1990). Such differences indicate a fundamental lack of reliable data on the major aspects involved in emissions.

The methodology and the underlying assumptions used to generate the estimates also produce sharply different results. The INPE (1990) report gives two figures of deforestation in the Brazilian Amazon, i.e 17,000 and 25,000 sq. km. per year depending on the set of assumptions one prefers to use on pre-1978 historical deforestation rates. Mahar (1989) in two different reports gives estimates of 48,000 and 80,000 sq. km. per year for the same Brazilian Amazon deforestation based on a report by Seltzer (1988) to INPE on total area burnt in 1988. Although the five-fold discrepancies are not the norm in the tropical countries, different studies have produced significantly different estimates for most countries. A more recent study (Dixon *et al,* 1994) using latitudinal classification of the world ecosystems gives a deforestation estimate of 154,000 sq. km. per year for the low latitudes (0° to 25°). Although it is not directly comparable to past estimates, it gives an indication that the global estimates are beginning to stabilize.

The variation in estimates of rates of deforestation, together with the imprecision in the estimates of the other variables have led to different estimates of consequent carbon stocks and flux. For example, the carbon flux from tropical forestry (billions of metric tonnes (Gt)), as estimated by various researchers show a wide variation.

Author	Carbon flux (Gt)
Molofsky *et al* (1984)	0.6 - 1.1
Houghton *et al* (1985a, 1987)	0.9 - 2.5
Detwiler & Hall (1988b)	0.4 - 1.6
Hao *et al* (1989)	0.9 - 2.5
Myers (1989)	0.4 - 1.4
Seiler *et al* (1980)	0.4 - 1.2
Dixon *et al* (1994)	1.2 - 2.1

By comparing results of several studies, Detwiler and Hall (1988a) found that the carbon release estimates vary significantly depending on the method of biomass data collection. A low estimate of 0.42 Gt of carbon release based on inventory volume data was obtained, compared to a high of 1.55 Gt based on destructive sampling data. In their own simulation, the estimate for carbon flux based on volume was 36 percent lower than that based on destructive sampling. Although more recent estimates such as Myers' for 1989 show a closer range, i.e 2.0 - 2.8 Gt, the bases for the uncertainty remain unchanged. Houghton (1990) gives an estimate of 1.1 - 3.6 Gt of carbon flux a year depending on the estimates of conversion of tropical forests to other landuses.

An attempt to improve the precision of estimates, was proposed at the IPCC meeting in Sao Paulo in 1990, by creating a network of scientists resident in the main deforesting countries who will use a common framework to estimate the emissions and uptake for each one of the countries (Graca *et al*, 1990). In the process, areas of severe data deficiency would be identified and effort be made to generate more accurate data in these areas. On these grounds, the model described in this Appendix was developed as a common tool to assist the scientists in the respective countries to undertake the estimation for the individual countries. The results will then be used to assess the climatic and socio-economic implications of the carbon budget emanating from each country's current and likely future landuse and forest management policies.

STRUCTURE OF COPATH

General Description

The model described here is a framework for calculating carbon emissions and sequestration based on connected spreadsheets. It is designed for use in either SYMPHONY or LOTUS 1-2-3 computer programs, and can be run on any PC or Compatible with at least a 286 (or equivalent) microprocessor. Using the lowest computing capability allows for a wider use of the framework in a region which is not awash with latest computing technologies. On the other hand, the need for wide application leads to a Random Access Memory (RAM) constraint, which partially dictated the current structure of the model. COPATH borrows its name from the initials of the constituent modules upon which the inter-connected spreadsheets are based.

The model is divided into two main parts - BASIS and FORECAST. The first part takes specific information about the forest and computes stored carbon, emissions and sequestration for a desired base year. The second part takes the base year estimates and by applying various assumptions on the future states of the forest resource and consumption of forest products, it forecasts the extent of future carbon emissions and uptake from the forest sector. Four major conversion modes are accounted for in this framework.

The FORECAST is subdivided into four modules which undertake the computation for each major mode of deforestation i.e, conversion to agriculture (AGRIC), conversion to grazing land (PASTURE), various management regimes guiding forest harvesting policy (HARVEST), other landuses such as dams, roads, mining, re-conversion of non-forest land to forests, and forest fires, human settlements, etc (OTHER). The totals for each module are extracted and summed-up to obtain the emissions and uptake for any given forest type (life zone). The process is repeated for each life zone and then added up for the country as a whole. A biome-wide aggregation can then be obtained from these individual country estimates, provided that the level of imprecision in each estimate is comparable.

Description of BASIS

This portion of the program computes carbon emissions and uptake for the base year, consequent from existing policies regarding the use of the forest estate. In future versions of the model, current emissions from past deforestation and sequestration by non-mature growing-stock will be included to account for the carbon implications of past forest landuse policies.

The forest in a given country is classified into various life zones such as the Holdridge (1967) classification which includes at least 9 zones found in the tropics. In most cases, the forest area is already classified in general life zones. Vegetation maps as constructed from both remote sensing sources and ground proofing are the basic tools in classifying the life zones. Satellite imagery is used in many countries to continuously monitor the state of the vegetation in the major forested countries in the world. The use of similar life zone classification for each country helps to increase the consistency of the estimates and makes zonal comparison and global aggregation possible.

In most countries, the life zones will breakdown into a few 'true' forests including montane, submontane, transitional and lowland types, swamp and terra-firma types, evergreen, semi-deciduous, equatorial and man-made forests. In some countries where locally unique ecosystems such as mangrove forests and man-made plantations cover significant areas, they will be treated as separate life zones for the purpose of this exercise. If a life zone is not geographically contiguous, or lies in more than one administrative units of separate record-keeping with respect to landuse, then the estimation may need to be repeated for the respective life zone in each administrative unit.

Determination of Stored Carbon

For each of the identified forest types, we want to find out the total amount of carbon stored upto and including the base year, in this case 1990. Any flux due to the use of forest land is therefore a measure of changes in this stock of carbon. The total stored carbon for that portion of the forest with destructive sampling data is computed by multiplying the dry biomass density with the carbon content of the dominant species, or a weighted average of the most common species in the representative area. It is imperative to point out that the use of area-weighted average biomass leads to biased estimates of carbon release as long as we use incomplete life zone classification while certain life zones are disproportionately preferred for various landuses such as agriculture or pasture (Detwiler *et al*, 1985). Destructive sampling data is very scanty and tends to be concentrated in a few medium moist life-zones (Brown and Lugo, 1982).

The most commonly available data are from inventory sampling of the above ground stem biomass. For the remainder of the forest area, inventory data deductive method *a' la* Brown and Lugo (1982, 1984, 1989) and Detwiler *et al* (1985, 1986, 1988) is used to estimate the total biomass and hence total stored carbon in the vegetation for each life zone. The following is a list of items required as input in the BASIC part of the model for computation of stored carbon from this sampling approach.

Stored carbon in the vegetation

-Total area (hectares) covered by forest type *i in base year t.*

-Dominant species covering forest type *I.*

This is required to compliment other species-specific data such as density, basal area, etc. If the species information is not sufficiently available, then the inventory and other information will be based on a weighted average of the known species' structure.

-Inventory (cubic meters per hectare).

The estimate of stemwood volume or merchantible timber provide a basis for estimating the total aboveground biomass. The volume is relatively stable for mature forests.

-Wood Density (tonnes per cubic meter).

The average wood density for the stem will be used to calculate total biomass of the forest. If unavailable, then wood density for the dominant species should be used. In many cases, the data on wood density exists for oven-dry wood of specified humidity.

-Stemwood Wet Biomass (tonnes per hectare).

This is the product of inventory and wet wood-density as given above.

-Ratio of Stem to Total Wet Biomass above-ground.

Each forest type has a different ratio of stem to total biomass above-ground due to the species composition and plant physiological characteristics. This data is obtained from destructive sampling methods which involve measuring the biomass of the respective flora above the ground.

-Ratio of Above-ground to Subterranean Biomass.

The amount of biomass in the roots varies a great deal depending on the species' rooting systems and on-site pedological properties. This information is also obtained from destructive sampling studies. Very few studies have been done for specific ecosystems and as such, the use of some average ratios from the few studies my be necessary.

-Ratio of Wet to Dry Biomass.

For converting the wet biomass to dry biomass estimate.

-Carbon Content of Dry Biomass.

This differs significantly among species, and small errors in this variable can lead to large errors in the estimate of carbon stock, emissions and sequestration. In the absence of this information, researchers have used 0.50 tC per ton of dry biomass.

By applying the four ratios to the stem wet biomass computed above, and then multiply by the area (hectares) covered by forest type in the base-year, we obtain the total amount of stored carbon for a given life zone upto the year of analysis. For mature forests, this amount is stable and does not change substantially unless destructive factors such as fire, botanical epidemics, or human activity interferes with the vegetation ecosystem. The total amount of stored carbon represents the maximum carbon which can be released into the atmosphere from the vegetation if and when deforestation takes place. Some significant amount of carbon stored in the soil will also be released during the conversion.

Soil carbon

Most of soil carbon of interest in this model originates from the soil organic matter. Deforestation reduces soil carbon content mainly through enhanced oxidation and erosion of the top soil. The estimate of soil carbon in forest ecosystems is very uncertain, and the few estimates of soil carbon in tropical forests show a very wide variation. Detwiler (1986) estimates that tropical soils contain between 52 and 67 tonnes of carbon per hectare and up to 40% is released within 5 years of clearing, depending on the subsequent landuse. Other studies have shown a wider variation depending on life zones covered and the depth of the profile used for the estimate. Pedological and soil chemistry studies are good sources of data for soil carbon content. If these data are unavailable for a given life zone, then estimates can be made based on zonal or country cross-sectional studies and then adjusted for pertinent local variates.

Determination of Released Carbon

When deforestation takes place, carbon is released in two stages. During the conversion year, some will be released through combustion and/or soil disturbance. In this version of the model, we are allocating all the soil carbon release to the year of conversion. In future versions, the soil carbon for each landuse category will be released over the appropriate number of years. The remainder of the biomass-based carbon is released over a period of time, mainly through decomposition. The amount of carbon released in each of the two stages depend on the mode of forest conversion and the type of use the biomass is put to. Whereas newsprint may decay in one to two years, it may take 50 to 100 years for structural wood to oxidize. We will therefore compute the release from each landuse conversion activity separately. If more than one method is active for a given area, the emissions from each will be proportionately summed up from the respective activity. All the four main landuse conversion modes have both prompt and residual release of carbon into the atmosphere. In this model, the sum of emissions from combustion and decomposition of biomass cleared in the current year together with release from soil disturbance is referred to as prompt release. The rest of the carbon released will be from annual decomposition, while the sequestered carbon is referred to as annual CO_2 uptake.

The treatment of emissions which are delayed over time increases the complexity of the estimation. For the base year, i.e, current year of emissions estimation, the amount of carbon dioxide released into the atmosphere due to landuse conversion in the past years will depend on the precision of our knowledge of the extent of deforestation in each of the past relevant years. In the ideal case, the emissions carried forward from the past will be the sum of all emissions expected to be released at time *t* from each of the preceding years which had a deforestation or forest utilization activity. Given the fact that our data on historical rates of deforestation and the relevant carbon stocks is inadequate, we need to use an approximation of the emissions carried forward from the past. In a case of a constant rate of change of land use, the historical emissions will approximately equal future emissions if the structure of forest product use with respect to duration of product use remains the same.

Different forest types and conversion activities may require different approximations due to the apposite variations which affect release. The residual release from the current year's vegetation removal will be distributed to future years, depending on the release processes.
In each conversion method which involves burning, a determination of the proportion of the biomass which is carbonized has to be undertaken due to the long carbon retention period involved. Field charcoal is estimated to withdraw carbon from this cycle for many centuries. The prompt and annual release described below is for the non-carbonized proportion of the biomass.

Agriculture

Three types of forest conversion to agriculture are considered in this model. Conversion to permanent agriculture is subdivided into annual and perennial crop lands. The area used for fallow agriculture is assumed to be used for annual crops only.

The method of conversion determines the amount and distribution of release. More soil carbon will be released in the annual crop than perennial crop cycle, and everything else being equal, the length of decomposition would be longer for the perennial crop area. Different areas employ varying levels of burning depending on the forest type, expected crop husbandry, duration of fallow, etc. On one extreme, the land is cleared and the biomass piled in bundles and left to rot, while in some dry areas, most of the vegetation is burnt with very little left for decomposition. We can use some average estimates of proportion released through combustion, decomposition and soil disturbance in the cases where no studies of release process have been done.

Pasture land

Two types of conversion to grazing land are recognized in this model, i.e permanent and fallow grazing land. In the first type, the forest is cleared and used for pasture as a permanent landuse, whereas in the latter case, the area is abandoned after being used for a given period due to any number of reasons. The prompt and residual release of carbon dioxide will be treated exactly the same as in the case of agricultural conversion. The difference is that the distributions of release from combustion, decomposition and soil disturbance will differ due to the kind of activity being undertaken on the land.

Harvesting and wood utilization

In this model, three harvesting regimes are recognized to have different carbon flow effects. They consist of clear-cutting followed by natural regeneration, clear-cutting followed by afforestation with man-made plantations, and selective cutting with natural reforestation. Each is further analyzed with respect to the intended use of the harvest, i.e logging for short-term wood use such as pulp, paper and woodfuel; and for long-term wood use such as timber extraction for structural wood.

The area being logged is assumed to have no prompt release due to combustion, and the biomass which may be used for wood fuel will appear under release from short-term product use. The prompt release in this case will be from soil disturbance and possible current year decomposition. The delayed release will come from both the decomposition of biomass left on the field and from oxidation of the wood in use. With the knowledge of the rate of growth of consumption of wood for long-term use, we compute the amount of release in year t from oxidation of wood in long-term use. Although the oxidation is residual, in this model we make a simplifying assumption that all the wood in long-term use will release its carbon at the beginning of the defined long-term period. Given the smooth nature of wood product consumption curve, the lump sum release assumption is not significantly distortive. To the extent that one knows the oxidation process for a given wood product end-use, the use of the appropriate decay function would reduce this distortion.

The release from short-term wood use is assumed to be equally distributed over the length of the short-term period. Various product types may be classified into different short-terms depending on their specific length of use. Woodfuels and newsprint may be considered to be very short term, with an average life span of 3 years, while paper and paperboard may last for 10 years. Harvesting for exports is not treated any differently from that portion used for domestic consumption. The exported timber would be assumed destined for its historical use in the importing country, and the oxidation is tracked as if the wood was used in domestic consumption. Although this assumption helps to track all emissions from a given forest use, it does not address the crucial issue of assigning responsibility for the carbon emissions between the wood exporter and importer.

Other landuses and forest fires

This mode of deforestation will include the area used for dams and reservoirs, communication lines such as roads and railways, mining and human habitation such as permanent villages, towns and other physical facilities. Also included here are those areas from all the other modes which become permanently denuded, with little or no regrowth of vegetation.

The prompt release from other landuses is a sum of soil carbon release and a proportion of the biomass which may be used immediately or combusted. This varies depending on the specific landuse. The proportion left behind is assigned to future decomposition. In some cases such as dams, a great deal of the stored carbon is trapped for many years. Each case has to be treated with own merits.

Crown forest fires which burn a significant portion of the woody vegetation release large amounts of CO_2 whenever they happen. The proportion which is carbonized is withdrawn from the carbon cycle for a long time. Some researchers estimate that the charcoal is not oxidized for up to 1000 years (Suntharalingam *et al*, 1990). However, consequent fires may lead to the smoldering of part or all of the previously carbonized biomass. Forest fires also release other greenhouse gases such as nitrous oxide. The area which is burned and the proportion of the woody vegetation which is affected is estimated in this mode. The non-woody vegetation which will regrow in a period of a year is not considered as source of net carbon emission in this case. However, this portion is essential if one is estimating emissions of the other relevant greenhouse gases such as methane and nitrous oxide. If one of the other conversion activities modes such as harvesting is also affected by forest fires, a downward adjustment will need to be done on the released carbon.

Determination of Carbon Uptake

The amount of carbon sequestered after clearing of a forest vegetation and converting the area to another landuse depends on the type of vegetation which replaces the primary tropical forest. Research is still under way to find out the extent to which an increased concentration of atmospheric carbon may influence sequestration from its possible effects on plant growth (Shugart and Smith, 1990). Such CO_2 fertilization has been shown to occur in glasshouses, evidence of increased biomass accumulation in the field is still being sought. In this model, we assume that the growth of the subsequent vegetation is not influenced by the increase in atmospheric CO_2 concentration, and if evidence exists to that effect, this influence will be captured in the relevant estimates of net primary productivity used in estimating carbon uptake. In this model, the computation of carbon sequestration for each mode of landuse conversion will be done separately.

Agriculture

If the forest is converted into permanent agricultural land, then the uptake will depend on the kind of agricultural crop introduced. A long term woody crop such as rubber, coffee, cocoa, fruit trees, etc will be considered in some way to be similar to a tree crop and will (may) have a net uptake potential. In this case, the computation of CO_2 uptake will require data on the crops biomass dynamics and its husbandry. The carbon emissions and uptake for perennial agricultural crop after maturity will not be addressed in this model. Together with the land for permanent annual crops, this land will be left to the agricultural sector for the purposes of emissions. In any case, conversion to a non-woody annual crop leads to a negligible net carbon uptake, if any.

If the land is converted to swiddening type of farming, where after a number of years it is left fallow and reclaimed by natural secondary vegetation, then the computation of CO_2 uptake will be handled like the case of natural regeneration after the fallow period. In this case, we will need to use growth/yield studies to compute the change in biomass every year upto maturity of the secondary forest. A linear growth approximation may be adequate if we know the biological rotation age of the forest. In this program, we use linear growth curve because the deforestation and the subsequent landuse is a continuous process, and as such, summation of annual sigmoid growth curves over a rotation yields a linear growth approximation for the forest.

Estimates of the Mean Annual Increment (MAI) and carbon content of the ensuing vegetation can be obtained from studies of the neighboring secondary forest from past deforestation. In the absence of this data, adjusted biomass data for the outgoing primary forest can be used as a basis for the carbon uptake computation. If the MAI is given in volume per unit area, it has to be converted to weight per unit area using the average wood density of the secondary vegetation. The carbon uptake per unit area is the product of the MAI in tonnes per hectare and the carbon content of the secondary forest, multiplied by the stemwood to above ground biomass ratio, and the total to above ground biomass ratio as done in the carbon storage section above. Where direct estimates of net primary productivity (NPP) of the new land use is known, this provides a more accurate estimate of carbon sequestration.

Pasture land

For permanent pasture, the uptake potential is very small due to lack of woody vegetation. Any uptake resulting from growth of forage grasses will not be covered in this model. This can best be addressed within the animal husbandry sector. The uptake to be covered in this model comes from regrowth of abandoned or fallow pastures.

The speed and extent to which an abandoned pasture gets reclaimed by a natural forest differs depending on the pasture management regime preceding the abandonment (Uhl *et al*, 1988). To the contrary, there is evidence that some delicate ecosystems are so much ravaged they never achieve the biomass level prior to the deforestation (Serrao and Toledo, 1990; Saldariaga, 1987). The computation of carbon uptake by the regrowth will be done the same way fallow agriculture was handled above.

Harvesting and subsequent management regimes

The three harvest/management regimes discussed above have different carbon uptake streams. In the selective cutting case, we are assuming a natural regeneration of the biomass proportional to the amount removed. The uptake potential is therefore proportional to the extent of re-thickening of the forest.

In the case of clear-cutting followed by natural regeneration, the computation of CO_2 uptake takes the growth curve approach mentioned earlier. The third option is to replant the area with new or same species but in a plantation format, in most cases as a monocultural vegetation. The CO_2 uptake ramifications of afforestation are enormous because of the potential to amass a lot of biomass per unit area. Despite the larger biomass, the approach for computing uptake is essentially the same as for reforestation which was shown earlier.

Other landuses and forest fires

The CO_2 uptake of fire scorched areas is dependent on the frequency of the fires and the type of destruction caused. For annual fire areas, there is very little net uptake due to the type of vegetation burned. If it is a one time crown fire, the uptake implications is very similar to selective harvesting or clear-cutting and the options available for CO_2 uptake are the same. In this case, we equate the regeneration to a partial reforestation by a similar forest type. The activities included in other landuses do not provide for a new woody vegetation, and as such the CO_2 uptake is minimal. Permanently denuded lands from other conversion modes are a typical example.

Soil carbon uptake

In each of the four conversion modes, the soil carbon replenishment is treated in the same way. The NPP estimate should include the rate at which the soil carbon is being replenished after the conversion of the area. In the absence of this data, we assume that the soil carbon will be replenished over the lifetime of the new vegetation, and the new equilibrium will approximately be the same as the soil carbon before the conversion. To the extent that this assumption holds, the amount of soil carbon lost in the conversion will be regained, and the annual distribution can be assumed to mimics the vegetation growth pattern. Under different silvicultural and crop husbandry conditions, the new soil C may be less or exceed the prior equilibrium. Very little data exists about the dynamics of soil C replenishment in different landuse conversion modes.

Using the above described BASIS, the base year estimates of stored carbon, release and uptake is estimated for each forest type in the country and then aggregated to obtain the stock and flux from the countries forest sector. These estimates are used as input in the forecasting of future emissions and sequestration. In the following section we present the models and assumptions underlying the FORECAST portion of the program.

DESCRIPTION OF THE FORECAST

In this version of the model, sequestration by growing forests from past regeneration and afforestation as well as emissions from past deforestation and forest use are not being accounted for. This is due to our present emphasis on carbon implications of present and future policies on forest resource utilization. With knowledge of past deforestation and resultant landuses, it should however not be difficult to incorporate the historical emissions and uptake into this analysis.

The net CO_2 release is the sum of prompt release and emissions from annual decomposition, less the amount sequestered in the year under consideration. The prompt release mainly comes from combustion and soil disturbance. We assume that the soil carbon is released in the year of deforestation. Any initial decomposition of light biomass such as leaves, bark etc is also included in the prompt release estimate. The residual biomass which is not carbonized is assumed to decompose over a known period of time, and we assume equal release every year. The annual decomposition is therefore a cumulative amount from all past years due for release in year *t*. We assume that decomposition begins in year $t + 1$. The CO_2 uptake is assumed to begin in the base year and as described in the basis, the uptake is derived from an assumed linear growth curve for the new crop. Use of yield curves or NPP functions will yield a more accurate uptake trend, but we feel that the status of data availability in the biome justify the use of a more simple function.

The estimate of future net release is based on knowledge of deforestation in the base year, decomposition period, rate of growth of secondary vegetation, rotation age and the change in the rate of deforestation. If such estimates for future deforestation rate exists, they are used as direct inputs in the forecast module. In the absence of such estimates, the model assumes that due to the exhaustability of the forest resource, political pressure and environmental compulsion, the rate of deforestation will continue increasing commensurate to the growth of the deforestation pressures such as rural population, but will begin declining as the counter pressures assert themselves. The rate of increase and decline, including the turning point will be estimated by the researcher based on information exogenous to this model. For example, in the absence of any other estimate on rate of land use change, one can assume that the deforestation will increase at a decreasing rate, until the country reaches a point of sustainable forest management, as is now thought to be the case in many temperate countries.

Structure of the Forecasting Model

Net Carbon Release in Year t

The release and uptake for the base year is used to forecast future emissions. In general, the net carbon release for the country from all forest types in year *t* can be represented as:

$$\sum_{i=1}^{n} N_{it}=\sum_{i=1}^{n} [R_{it}+d_{it}-u_{it}]$$

where: i = forest type
n = number of forest types in the country
t = year of estimation

N = net carbon release
R = prompt release from combustion and/or soil disturbance
d = amount released from decomposition
u = carbon uptake.

Future Annual Estimates

The representation of the model can be simplified by describing the process in three various periods in the future, i.e base year to decomposition length, decomposition to biological rotation age and beyond the rotation age of the new crop. In this model, we are assuming that the rate of deforestation will be changing as a known proportion of the base year levels, and as such the prompt release, decomposition and uptake will follow similar behavior subject to the specific modes of uptake and release.

Period between base year and length of decomposition

During this period, the annual decomposition increases every year due to the residual emissions brought forward from previous years. Given the assumptions we used regarding the change in deforestation rate, the maximum net carbon release per year will be achieved during this period when p goes to zero. The net emissions for year t can be approximated by the following equation.

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} [r_i^{\alpha-1} R_{i0} + \frac{1-r_i^{\alpha-1}}{1-r_i}(d_{i0}-u_{i0})]$$

where:

p = percent change in deforestation from year t - 1
r = 1 + p
α = t - t_0 = number of years since base year
R_0 = carbon release during the base year
d_0 = initial annual carbon release from decomposition
u_0 = initial annual carbon uptake.

Period between length of decomposition and biological rotation

In this period, the annual decomposition is the sum of emissions from the past β years. The prompt release and uptake terms are same as in the period between base year and length of decomposition. It is during this period when net uptake starts to exceed release in the relevant modes of landuse conversion. The net release can be represented as:

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} [r_i^{\alpha-1} R_{io} + \frac{1-r_i^{\beta}}{1-r_i} r_i^{\alpha-\beta-1} d_{io} - \frac{1-r_i^{\alpha}}{1-r_i} u_{io}]$$

where:

β = Average decomposition period for the forest type.

Period beyond the biological rotation

The period after the new vegetation reaches biological maturity will have the same terms for prompt release and annual decomposition, but the uptake is modified due to the fact that as new crop reaches maturity, we assume that its CO_2 uptake is in equilibrium with release. The equation given below provides an approximate forecast of net emissions at any given year.

$$\sum_{i=1}^{n} N_{it} = \sum_{i=1}^{n} [r_i^{\alpha-1} R_{io} + \frac{1-r_i^{\beta}}{1-r_i} r_i^{\alpha-\beta-1} d_{io} - \frac{1-r_i^{\alpha}}{1-r_i} u_{io} r_i^{\alpha-\gamma-\delta}$$

where:

γ = the biological rotation age of the subsequent forest
δ = the fallow period before regeneration.

In all the three cases represented above, if $r = 1$, then the model becomes the same as the base-year scenario due to the divergent geometric series in the neighborhood of unity. In this case, we use ϵ (a very small number) instead of p to compute the net emissions.

CONCLUSION

In this Appendix we have discussed the problems associated to the existing estimates of carbon stock, emissions and sequestration in tropical forests. We then present a description of a spreadsheet model - COPATH intended for use in assisting researchers in various countries undertake consistent estimates for their countries. The model is simplified in many respects so as to allow for a wide application in countries where the users may not necessarily be experts in forestry and global climate change. The first part of the model is used for estimating carbon stocks, emissions and sequestration for a given base year, and the second portion is useful in forecasting future emissions and uptake under various landuse scenarios. The choice of the most likely scenario will provide an estimate of the carbon flux profile of the country's forest sector given a set of land use and forest utilization policies.

REFERENCES

Brown, S., A.J.R. Gillespie and A.E. Lugo. 1989. Biomass Estimation Methods for Tropical Forests with Applications to Forest Inventory Data. *Forest Science* 35(4): 881-902.

Brown, S. and A.E. Lugo. 1982. The Storage and Production of Organic Matter in Tropical Forests and their Role in the Global Carbon Cycle. *Biotropica* . 14(3): 161-187.

Brown, S. and A.E. Lugo. 1984. Biomass of Tropical Forests: A New Estimate Based on Forest Volumes. *Science* 223: 1290-1293.

Dixon, R.K. S. Brown, R.A. Houghton, A. M. Solomon, M.C. Trexler, J. Wisniewski. 1994. Carbon Pools and Flux of Global Forest Ecosystems. *Science* 263: 185-190.

Detwiler, R.P. 1986. Landuse Change and Global Carbon Cycle: The Role of Tropical Soils. *Biogeochemistry* 2: 67-93.

Detwiler, R.P., C.A.S. Hall and P. Bogdonoff. 1985. Landuse Change and Carbon Exchange in the Tropics II: Estimates for the entire Region. *Environmental Management*. 9: 335-344.

Detwiler, R.P. and C.A.S. Hall. 1988. Tropical Forests and the Global Carbon Cycle. *Science* 239: 42-47.

FAO/UNEP. 1981a. Tropical Forest Resources Assessment Project: Forest Resources of Tropical Africa, Part II: Country Briefs. FAO/UNEP. Rome.

FAO/UNEP. 1981b. Tropical Forest Resources Assessment Project: Forest Resources of Tropical Asia. FAO/UNEP. Rome.

FAO/UNEP. 1981c. Tropical Forest Resources Assessment Project: Los Recursos Forestales de la America Tropical. FAO/UNEP. Rome.

Goldemberg, J. 1990. Secretary of State for Science and Technology, Brazil. Personal communication, letter of May 22nd, 1990. Sao Paulo, Brazil.

Graca, M.G.G., A. Ketoff, W.R.L. Makundi, M.E.M. Helene, J. Ribot, J.Romm and J. Sathaye. 1990. Tropical Forestry and Global Climate Change: Background and Agenda for An International Research Network. *LBL Report* No. 35256 .

Hao, W.M., M.H. Liu, and P.J. Crutzen. 1990. In *Fire in the Tropical Biota* , J.G. Goldammer, Ed. (Springer-Verlag, Berlin).

Hodridge, L.R. 1967. Life Zone Ecology, rev. edn. Tropical Science Center, San Jose, Costa Rica.

Houghton, R.A. 1990. Tropical Deforestation and Atmospheric Carbon Dioxide. Woods Hole Research Center.

Houghton, R.A., R.D. Boone, J.M. Melillo, C.A. Palm, G.M. Woodwell, N. Myers, B. Moore, D.L. Skole. 1985. Net Flux of Carbon Dioxide From Tropical Forests in 1980. *Nature* 316: 617-620.

Houghton, R.A., R.D. Boone, J.R. Fruci, J.B. Hobbie, J.M. Melillo, C.A. Palm, B.J. Peterson, G.R. Shaver, G.M. Woodwell, B. Moore, D.L. Skole. 1987. The Flux of Carbon from Terrestrial Ecosystems to the Atmosphere in 1980 due to Changes in Landuse: Geographic Distribution of the Global Flux. *Tellus* 39B: 122-139.

Mahar, D. 1989. Government Policies and Deforestation in Brazil's Amazon Region. The World Bank. Washington D.C., U.S.A.

Melillo, J.M., C.A. Palm, R.A. Houghton, G.M. Woodwell, and N. Myers. 1985. A Comparison of Two Recent Estimates of Disturbance in Tropical Forests. *Environmental Conservation.* 12:37-40.

Molofsky, J., C.A.S. Hall, and N. Myers. 1986. Comparison of Tropical Forest Surveys. U.S. Department of Energy, Washington D.C, U.S.A.

Molofsky, J., E.S. Menges, C.A.S. Hall, T.V. Armentana and K.A. Ault. 1984. The Effects of Landuse Alteration on Tropical Carbon Exchange. In T.N. Veziraglu, ed., *The Biosphere: Problems and Solutions* : 181-184. E.S.P. Amsterdam, Netherlands.

Myers, N. 1980. Conversion of Tropical Moist Forests (Report to the National Academy of Sciences). National Research Council, Washington D.C., U.S.A.

Myers, N. 1984. The Primary Source: Tropical Forests and our Future. W.W. Norton, London, U.K. & New York, U.S.A.

Myers, N. 1985. Tropical Deforestation and Species Extinction: The Latest News. *Futures* 17:451-463.

Myers, N. 1988. Tropical Deforestation and Remote Sensing. *Forest Ecology and Management* 23: 215-225.

Myers, N. 1989. Deforestation Rates in Tropical Forests and Their Climatic Implications. (A Friends of the Earth Report). London, U.K.

Saldariaga, J.G. 1987. Recovery Following Shifting Cultivation: A Century of Succession in the Upper Rio Negra. In *Amazonian Rain Forest: Ecosystem Disturbance and Recovery* . C.F. Jordon, Ed. (Springer-Verlag, New York), pp 24-33.

Seiler, W. and P.J. Crutzen. 1980. Estimates of Gross and Net Fluxes of Carbon Between the Biosphere and the Atmosphere from Biomass Burning. *Climate Change* 2: 207-247.

Serrao, E.A.S. and J.M. Toledo. 1990. Sustaining Pasture-based Production Systems for the Humid Tropics. In *Development or Destruction of the Livestock Sector in Latin America.* , T. Downing, S. Hecht and H. Pearson, Eds. (Westview, Boulder, Colorado).

Setzer, A.W., M.C. Pereira, A.C. Pereira Jr. and S.A.D. Almeida. 1988. *Relatorio de Atividades do Projecto* . IBDF-INPE 'SEQE' - Ano 1987. (Unpublished Report).

Shugart, H.H. and T.M. Smith. 1990. Implications of Climate Change for Global Forest Ecosystems. University of Virginia, Chalottesville, Virginia.

Singh, K.D. 1988. Comments on Tropical Deforestation and Remote Sensing. *Forest Ecology and Management.* 24: 312-313.

Suntharalingam, P., B. Braatz and B. Pepper. 1990. A Report to U.S. E.P.A. Baseline Case for Landuse Change Model. Washington D.C.

Uhl, C., R. Buschbacher and E.A.S. Serrao. 1988. Abandoned Pastures in Eastern Amazonia. Patterns of Plant Succession. *Journal of Ecology*, 76: 663-681.

GLOSSARY

Afforestation - Planting of new forests on lands which, historically, have not contained forests. These newly created forests are included in the category "Managed Forests" in the Land Use Change and Forestry module of the emissions inventory calculations. See also reforestation.

Albedo - The surface reflectivity of the globe. Affects the amount of solar radiation being radiated back into space without being absorbed by the earth's climate system.

Anthropogenic emissions - Emissions resulting from human activities.

Appliance - Any household energy-using device.

Base year - The year for which the inventory is to be taken. This is currently 1990. In some cases (such as estimating CH4 from rich production) the base year is simply the last year of a number of years over which an average must be taken.

Biodiversity - Biological diversity, i.e., the variety of species in a given area.

Biofuels - Wood, waste, and alcohol fuels.

Biomass - Organic material both above the ground and below ground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots etc. When burned for energy purposes, these are referred to as biomass fuels.

Biosphere - Refers to the zone of the earth and atmosphere that contains living organisms. The terrestrial biosphere excludes the oceans.

Bottom Up Modeling - A modeling approach which arrives at economic conclusions from an analysis of the effect of changes in specific parameters on narrow parts of the total system.

Carbon tax - A tax on fossil fuels based on the individual carbon content of each fuel. Under a carbon tax, coal would be taxed the highest per MBtu, followed by petroleum and then natural gas.

Carbon cycle - General term used in reference to the sum of all reservoirs and flows of carbon on Earth. The flows tend to be cyclic in nature; for example, carbon removed from the atmosphere (one reservoir) and converted into plant tissue (another reservoir) is returned back into the atmosphere when the plant is burned.

Carbon reservoir or sink. Within the carbon cycle, the physical site at which carbon is stored (e.g., atmosphere, oceans, Earth's vegetation and soils, and fossil fuel deposits).

CFCs (Chlorofluorocarbons) - A family of inert gases, including CFC-11, CFC-12, and CFC-113.

Climate - The statistical collection and representation of the weather conditions for a specified area during a specified time interval (usually decades).

Closed Forest - A dense forest with closed canopy through which sunlight does not penetrate sufficiently for grasses to grow on the forest floor. These forests contain a significantly greater amount of biomass per hectare than open forests.

Cogeneration: The simultaneous generation of both electric power and heat; the heat, instead of being discharged without further use, is used in some fashion (e.g., in district heating systems).

Cultivar - Variety of plant species.

Deforestation - Converting forest land to other vegetation or uses (e.g., cropland, pasture, dams).

Degradable Organic Carbon - Organic material which can decay, expressed as weight of carbon. Usually 15 to 25% of total waste.

Demand-side management- The planning, implementation, and monitoring of utility activities designed to encourage customers to modify their pattern of electricity usage.

Discount rate: The rate at which money grows in value (relative to inflation) if it is invested.

Dynamic - In the field of modeling, a dynamic model includes inter-temporal relations between variables. A model that does not include such relations is called static.

Dynamic Programming - A method to find an optimal time path.

Emission Factor - A coefficient that relates actual emissions to activity data as a standard rate of emission per unit of activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions.

Endogenous variables - Variables determined within the system under consideration.

Energy Forms and Levels - Primary energy is energy that has not been subjected to any conversion or transformation process. Secondary energy (derived energy) has been produced by the conversion or transformation of primary energy or of another secondary form of energy. Final energy (energy supplied) is the energy made available to the consumer before its final conversion (i.e., before utilization). Useful energy is the energy made usefully available to the consumer after its final conversion (i.e., in its final utilization).

Energy intensity - The amount of energy required per unit of a particular product or activity.

Energy services- The service or end use ultimately provided by energy. For example, in a home with an electric heat pump, the service provided by electricity is not to drive the heat pump's electric motor but rather to provide comfortable conditions inside the house.

Engineering Approach - A particular form of bottom-up modeling in which engineering-type process descriptions (e.g., fuel efficiency of end-use devices) are used to calculate a more aggregated energy demand. This term is particulary used in contrast to econometric models.

Enteric fermentation - The intestinal fermentation which occurs in ruminant animals such as cows; it is a major biological source of methane.

Exogenous Variables - Variables which are determined outside the system under consideration. In the case of energy planning models, these may be political, social, environmental, and so on.

Feedback - When one variable in a system (e.g., increasing temperature) triggers changes in a second variable (e.g., cloud cover) which in turn ultimately affect the original variable (i.e., augmenting or diminishing the warming). A positive feedback intensified the effect. A negative feedback reduces the effect.

Fossil fuel - Coal, petroleum, or natural gas or any fuel derived from them.

General Equilibrium Analysis - An approach which considers simultaneously all the markets in an economy, allowing for feedback effects between individual markets. It is particularly concerned with the conditions which permit simultaneously equilibrium in all markets, and with the determinants and properties of such an economy-wide set of equilibrium.

Greenhouse Effect - An atmospheric process by which greenhouse gases (such as CO_2, CH_4, N_20, and CFCs) affect the global energy balance. Shortwave radiation from the sun that reaches the earth and is re-emitted as long wave infrared radiation is partially absorbed by greenhouse gases (GHGs). In the absence of GHGs the earth's average temperature would be 18° C rather than 15° C .

Greenhouse gas: Any gas that absorbs infrared radiation in the atmosphere.

GWP (Global Warming Potential - Some greenhouse gases are more effective, on a unit basis, of affecting, or forcing," the climate system. The GWP combines the capacity of a gas to absorb infrared radiation and its residence time in the atmosphere with a time frame of analysis, then expresses the result relative to CO_2.

Income elasticity - The expected percentage change in the quantity demand for a good given a one percent change in income. An income elasticity of demand for electricity of 1.0 implies that a one percent increase in income will result in a one percent increase in demand for electricity.

Input-Output Analysis - Method of investigating the interrelationship between the branches of a national economy in a specific time period. The representation, in the form of a matrix table is called an input-output table. An input-output analysis allows the changes in total demand in related industrial branches to be estimated.

Least-cost planning - In energy planning, the practice of basing investment decisions on the least costly option for providing energy services. It is distinguished from the more traditional approach taken by utilities, which focuses on the least costly way to provide specific types of energy, with little or no consideration of less costly alternatives that provide the same energy service at lower costs.

Life cycle cost - The cost of a good or service over its entire life cycle.

Linear Programming - A practical technique for finding the arrangement of activities which maximizes or minimizes a defined criterion subject to the operative constraints. For example, it can be used to find the most profitable set of outputs that can be produced from a given type of crude oil input to a given refinery with given output prices. The technique can deal only with situations where activities can be expressed in the form of linear equalities or inequalities, and where the criterion is also linear.

Macroeconomics - The study of economic aggregates and the relationships between them. The targets of macroeconomic policy are the level and rate of change of national income (i.e., economic growth), the level of unemployment, and the rate of inflation. In macroeconomics, the questions about energy are how its price and availability affect economic growth, unemployment, and inflation; and how economic growth affects the demand for energy.

Manure - Waste materials produced by animals that are managed for agricultural purposes. When manure is managed in a way that involves anaerobic decomposition, significant emissions of methane can result.

Marginal Costs - In a Linear Programming Environment, this term has the very specific meaning of change of the objective function value as a result of a change in the right-hand-side value of a constraint. If, for example, the objective is to minimize costs, and if the capacity of a particular energy conversion facility, such as a power plant, is fully utilized, the marginal cost in the LP sense expresses the (hypothetical) reduction of the objective function value (i.e., the benefit) of an additional unit of capacity.

Market clearing - The economic condition of supply equalling demand.

Open forests - Open forests are less dense than closed forests, do not have a closed canopy and have grasses growing on the forest floor. These forests contain less biomass per hectare than closed forests.

Optimization Model - A model describing a system or problem in such a way that the application of rigorous analytical procedures to the representation results in the best solution for a given variable(s) within the constraints of all relevant limitations.

Price elasticities - The expected percentage change in quantity demand for a good given a one percent change in price. A price elasticity of demand for electricity of -0.5 implies that a one percent increase in price will result in a half percent decrease in demand for electricity.

Radiative forcing - Changes in the global balance of incoming solar radiation and outgoing infrared radiation caused by a radiative forcing agent, such as clouds, surface albedo, and greenhouse gases. This results in changes in the global climate.

Reforestation - Planting of forests on lands which have, historically, previously contained forests but which have been converted to some other use. Replanted forests are included in the category "Managed Forests" in the Lands Use Change and Forestry module of the emissions inventory calculations. See also afforestation.

Renewable energy - Energy obtained from sources that are essentially inexhaustible (unlike, for example, the fossil fuels, of which there is a finite supply). Renewable sources of energy include wood, waste, wind, geothermal, and solar thermal energy.

Retrofit - To update an existing structure or technology by modifying it, as opposed to creating something entirely new from scratch. For example, an old house can be retrofitted with advanced windows to slow the flow of energy into or from the house.

Ruminant animals - Herbivores (grazing animals such as cattle, buffalo, sheep, goats, and camels) which have a large free stomach or rumen. Digestion in anaerobic conditions in the rumen can create significant emissions of methane from ruminant animals.

Scenario - Coherent and plausible combination of hypotheses, systematically combined, concerning the exogenous variables of a forecast.

Sensitivity Analysis - A method of analysis which introduces variations into a model's explanatory variables in order to examine their effects on the explained.

Sequester - To isolate and remove something. As used here, the processes by which carbon dioxide is removed from the atmosphere and retained for some period in a carbon reservoir (e.g., trees).

Simulation Model - Descriptive model based an a logical representation of a system, and aimed at reproducing a simplified operation of this system. A simulation model is referred to as static if it represents the operation of the system in a single time period; it is referred to as dynamic if the output of the current period is affected by evolution or expansion compared with previous periods. The importance of these models derives from the impossibility or excessive cost of conducing experiments on the system itself.

Sustainable - A term used to characterize human activities that can be undertaken in such a manner as to not adversely affect the environmental conditions (e.g., soil, water quality, climate) necessary to support those same activities in the future.

Temperate - Relating to the region between the tropics and the polar circles (between 23.5° and 66.5°) in both hemispheres.

Top-Down Modeling - A modeling approach that proceeds from broad, highly aggregated generalizations to regionally and/or functional disaggregated details.

Tropical - Relating to the region between the Tropic of Cancer and the Tropic of Capricorn, 23.5° North and 23.5° South, respectively.

User Interface - All information, including push-button help texts, facilitating the technically correct operation of a computer program.